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RESEARCH ARTICLE

Fiscal decentralization, local government environmental protection preference, and regional green innovation efficiency: evidence from China

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Abstract

Green technological innovation has gained in importance in regional policy making towards gaining competitive advantage and sustainable development. This paper used the data envelopment analysis method to calculate regional green innovation efficiency in China, and empirically tested the effect of fiscal decentralization through Tobit model. The regression results show that the local governments with higher fiscal autonomy would prefer to strengthen environmental protection; thus, the regional green innovation efficiency was improved. After the guidance of relevant national development strategies, these effects became more apparent. Our research provided theoretical support and practical guidance for promoting regional led green innovation, improving environmental quality, achieving carbon neutrality, and promoting the high-quality and sustainable development.

Keywords Data envelopment analysis · Fiscal decentralization · Local government environmental protection preference · Mediation effect · Regional green innovation efficiency · DEA model · Tobit model

JEL code H11 · Q55

Introduction

In the past decades, many developing countries such as China have achieved rapid industrialization but environmental pollution problems at the same time, so as to long-term unsustainable development troubles. According to the Chinese government, more than three quarters of Chinese cities exceeded the air quality levels deemed unhealthy in 2015, and GDP growth began to slow since 2012 as environmental damage and law of large numbers occurred and marginal returns on investment declined. As a response, Chinese government has brought environmental protection into its national development strategy such as the "12th Five-Year Plan," and at the 75th United Nations General Assembly in September 22th, 2020, China declared to achieve peak carbon dioxide emissions before 2030 and carbon neutrality before 2060. For the sake of green development, the role of green innovation is indispensable, and received many countries and regions' attention to gain competitive advantages (De Medeiros et al. 2014; Tariq et al. 2017). Through promoting the transformation of development mode, green innovation becomes a new source to drive high-quality development.

Green innovation efficiency (GIE) measures the input–output relationship of green innovation activities. The higher of the efficiency value means the less input and higher output (Xu and Zhou 2021). In order to analyze the regional GIE, we chose China as the sample because of its unbalanced regional development. Based on Chinese data, we calculated the regional GIE in provinces and examined the development characteristics and determinants. These research can help us explore ways to improve green innovation, strengthen global environmental governance, achieve carbon neutrality and carbon peaking, and maintain the sustainable development.

Due to the externalities of environmental cost and technological innovation, the market mechanism cannot be

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relied upon to autonomously drive sustainable development. Therefore, government intervention is particularly important. With the information advantages, local governments can provide more suitable development environment by providing favorable public goods and services (Filippetti and Archibugi 2011). Previous studies found that fiscal decentralization can enable local authorities to enjoy a high degree of environmental management, then improve the environmental innovation (Zhou et al. 2020). However, some researchers put forward the opposite view, arguing that with a higher fiscal autonomy, local officials may pay attention to short-term economic growth and eschew the public products with externalities such as technology and the environment protection, and thus detrimental to the urban innovation (Yang et al. 2020). In general, there are few studies on the causality between fiscal decentralization and regional GIE directly, and conclusions varied widely. As a highly centralized country, China's fiscal system has its particularities. In China, the central government possesses most of the fiscal authority, with remaining fiscal authority delegated to the local governments. Under such a background, China's special fiscal system and the characteristics of regional development provide us with a valid research sample to examine how fiscal decentralization affects the regional GIE.

This paper used the data envelopment analysis (DEA) method to calculate China's provincial-level regional GIE from 2007 to 2015, and studied the causality between fiscal decentralization and regional GIE, as well as revealed the important role and logical process of the fiscal system and government preference. The marginal contribution are as follows. First, we analyzed the direct impact of fiscal decentralization on regional GIE, and innovatively used local government environmental protection preference as an intermediary variable to analyze its medium mechanism. Second, we enriched the measurement methods of regional GIE by adopting the non-perspective SBM model and the three-stage DEA model. Third, we verified the important guiding role of the national development strategy direction on the behavior of governments, which may be the key to make full use of these effects.

The rest of the content are structured as follows. The next part is the institutional background, which introduced China's fiscal system. The third part is literature review and research assumptions, which summarized the previous measurement methods of regional GIE, the related research status of the relationship and causality among fiscal decentralization, local government environmental protection preference, and regional GIE, as well as put forward the research hypothesis. The fourth part is the method and empirical design, introducing the DEA method, constructing the econometric equation, and explaining the measurement method, sample selection, and data source of each variable. The fifth and sixth parts are the empirical results and discussion, which analyzed whether fiscal decentralization significantly affected regional GIE, revealed the mechanism of local government environmental protection preference, and the guiding role of the national development strategy direction. The seventh part is the conclusion.

Institutional background

Fiscal decentralization allocates fiscal autonomy between the different level governments by dividing financial authority and liabilities. Early fiscal decentralization theories were researched by Hayek (1945), Tiebout (1956), Musgrave (1959), Oates (1972), and others. In short, their view was that if local governments were given more autonomy, then intergovernmental competition would force the local officials to supply public products that are more consistent with the preferences of residents. Since 1994, The Chinese government has established tax-sharing system to divide their fiscal revenue and expenditure, and the "decentralization" of Chinese fiscal system has gradually taken hold. Then, the local governments have gained some independent decision-making power in fiscal revenue and expenditure to some degree.

Afterwards, more and more researchers studied the causal relationship between fiscal decentralization and economic growth, environmental quality or financial development, etc. (Hao et al. 2020; Jin and Zou 2005; Wang et al. 2021; Zhang and Zou 1998). Because of the information superiority, local governments with greater fiscal autonomy can provide higher quality public goods and services. However, other researchers believed that fiscal decentralization may promote vicious competition among local governments. Especially in recent years, the evaluation and selection criteria of Chinese government officials have changed from political performance to economic performance, forming a system of performance evaluation and official promotion centered on GDP, thus giving local governments strong incentive in pursuit of economic growth. Under China's special "political centralization + economic decentralization" model, in order, local governments adopt competitive strategies such as reducing tax burden and lowering environmental quality standards to attract the inflow of resources, which may lead to environmental deterioration and impeding the long-term sustainable development in their jurisdictions.

Literature review and research hypotheses

Regional GIE and its calculation

When green innovation was proposed by Fussier and James (1996), it was defined as a new product and technology that

can reduce the burden on the environment while providing value. Mink (1998) proposed that green innovation is to merely taking into account the ecological dimension in the production and operation of enterprises, while Beise and Rennings (2005) put forward that green innovation is a long-term implementation of projects that can improve environmental quality. It could be seen that green innovation is a relatively broad concept. Any creative and value added activity that can conserve resources and improve the environment quality would qualify as "green innovation." However, there are still inconsistencies in the definition of green innovation and similar concepts exist such as environmental innovation, sustainable innovation, and ecological innovation. Although there are subtle differences between these concepts, they are basically used interchangeably (Schiederig et al. 2012).

Regional GIE emphasized the use of input as less as possible and obtain more output in the green innovation activities, and the commonly used method to measure regional GIE is to construct an input–output index system, using the radial or non-radial DEA model for calculation (Li 2019). Some studies also used the super-SBM model, DEA-Malmquist model, three-stage DEA model, and other methods (Du et al. 2019; Liu et al. 2021; Luo et al. 2019; Wu 2021). In terms of index selection, although the index systems constructed by different researchers were different, a common practice was to use full-time equivalent of research and experimental development (R&D) personnel, internal expenditure of R&D funds and comprehensive energy consumption as input indicators, the number of patent granted and the new product sales revenue as expected output, and the composite index formed by the three industrial wastes (industrial waste gas, wastewater discharge\, and industrial solid waste generation) as unexpected output (Liu et al. 2019; Long et al. 2020; Xu and Zhou 2021).

Fiscal decentralization and regional GIE

Previous researches have found that in order to gain political promotion (Denise et al. 2017), strive for transfer payments from superior governments (Borge et al. 2014), and seek rent and sectoral interests (Tan and Zhou 2015), local officials with higher fiscal autonomy may emphasize production, ignoring innovation and environmental protection (Que et al. 2018; Sacchi and Salotti 2016), resulting in inhibiting the urban innovation (Yang et al. 2020). However, other researchers believed that under pressure to improve regional environmental quality, local government with higher fiscal autonomy would increase sewage charges and financial expenditures for pollution control (He 2015; Lo 2015), thereby promoting environmental innovation (Zhou et al. 2020). Based on the Brazilian manufacturing industry data, other researchers also found that financial tools such as taxation incentives and financial subsidies were effective in promoting green innovation (Gramkow and Anger-Kraavi 2017). To sum up, previous research works mainly concentrate on the impact of fiscal decentralization on urban innovation, environmental protection, and green innovation, with varied conclusions. The key to these differences lies in whether local governments were motivated to sacrifice the environment quality to boom the economy or to improve the environment quality after gaining higher fiscal autonomy. Therefore, the critical point lies whether local governments have environmental protection preference.

Fiscal decentralization and local governments environmental protection preference

As mentioned above, the impact direction of fiscal decentralization on regional GIE mainly depends on whether local governments have the motivation to use fiscal resources to strengthen local environmental protection after obtaining higher fiscal decentralization. Related literature shows that the central government of China is attaching increasing importance to environmental issues and has adopted a series of environmental protection measures, such as including environmental quality into the assessment of local officials (Sheng et al. 2019), and green development into the national development strategy named "five development concepts" (Xie 2013). In this context, with the increase of fiscal decentralization, local governments pay more attention to environmental protection issues, and increase fiscal environmental input and environmental administrative charge (Kuai et al. 2019), which indicates that fiscal decentralization will indeed improve local governments' preference for environmental protection.

Local government environmental protection preference and the regional GIE

The relative research on local government environmental protection preference and regional GIE found that strict environmental regulation would push companies to carry out green innovation (Zhang and Xu 2019), improve low-carbon technology innovation performance (Bi et al. 2016), but other researchers believed that different regulations types had different effects, such as market-based regulations could significantly stimulate GIE (Bi et al. 2020). Some researchers also conducted a comprehensive study of fiscal decentralization and environmental supervision and found that environmental supervision was likely to significantly promote the ecological innovation by enterprises, but when fiscal decentralization was taken into account, environmental regulation significantly inhibited enterprise ecological innovation (You et al. 2019). In all, most researchers supported the view that local governments' environmental preference could promote regional green innovation.

Research hypothesis

Improving the regional GIE is conducive to implementing green and innovative development, enhancing innovation and environmental protection capabilities, and promoting high-quality development, which in turn drives regional economic growth. Therefore, local officials have the excitation to improve regional GIE. Overall, fiscal decentralization can boost regional GIE from two perspectives. First, local governments often have information advantages in their jurisdictions, and have a better understanding of the public goods and services that are required by the regional development and the local people's preferences. Therefore, fiscal autonomy is beneficial to guarantee the flexibility and efficiency to make timely adjustments to the supply of public products. According to the changes of regional GIE activities, timely and accurate responses can be made to provide more accurate public goods supply for regional green innovation activities and improve resource allocation. And the output of GIE activities is tracked and evaluated in time to improve regional GIE. Second, under the guidance of the five development concepts and high-quality economic development policies from central government in China, local government officials are motivated to improve regional environmentally friendly and innovative development. Under the featured local government official promotion championship mechanism, local governments have incentives to promote regional GIE, and fiscal decentralization enables local authorities to gain greater financial autonomy to achieve that. Accordingly, we propose the first hypothesis as follows.

Hypothesis 1: Fiscal decentralization is conducive to improving the regional GIE.

Local governments with higher fiscal autonomy could allocate financial resources more flexibly according to their own preferences. Under the promotion assessment mechanism for government officials centered on green GDP and green development strategy from central government, local governments will increase their support and investment on regional environmental protection, monitoring, and publicity. The local authorities' preference for environment protection will signal to market participants that it attaches importance to green development, drive social resources to invest in environment protection, raise the research in green technology, and then improve the level of regional GIE. Thereby, we propose the second hypothesis as follows.

Hypothesis 2: Local government's preference for environmental protection is an intermediate mechanism through which fiscal decentralization affects regional GIE. Thus, fiscal decentralization can improve regional GIE by increasing local government's preference for environmental protection.

Methods

Data envelope analysis

DEA can measure the production efficiency by synthesizing various indicators. Among the traditional DEA method, the radial type model requires the output and input to be increased and decreased proportionally, which will lead to the ignoring of relaxation problem, and the non-radial models such as the SBM model allows a non-proportional reduction (or increase) of the input (or output), thus avoiding the drawbacks of the radial model. In addition, the DEA angular model mainly refers to the guiding angle of input or output. Different model angles will lead to differences in the calculated efficiency values, while the non-angular model can avoid this problem. Therefore, the non-radial, non-angular SBM model is more accurate and effective for efficiency evaluation than other traditional DEA models and more suitable for our research objects. The calculation formula of SBM model is shown as Eq. (5) in Appendix.

However, with the development of the DEA, researchers found that the SBM model, as a single-stage DEA model, fails to consider the influence of environmental factors and random factors on the efficiency value, while the three-stage DEA proposed by Fried et al. (2002) can. The relative calculation formulas of three-stage DEA model are shown as Eqs. (6)–(7) in Appendix.

Empirical model

Based on Hypothesis 1, we set the model as Eq. (1).

$$gie_{it} = \beta_0 + \beta_1 fd_{it} + \sum\nolimits_k \beta_k control_{it}^k + \varepsilon_{it} \quad (1)$$

In formula (1), gie_{it} represents the regional GIE value. fd_{it} represents the fiscal decentralization, and $\mathrm{control}_{it}^k$ represents control variables. ε_{it} is the error term.

In addition, based on Hypothesis 2 and referring to Baron and Kenny (1986), we adopted the stepwise regression method to test. Accordingly, the formula (2), formula (3), and formula (4) are set as follows.

$$lep_{it} = \lambda_0 + \lambda_1 fd_{it} + \sum\nolimits_k \lambda_k control_{it}^k + \varepsilon_{it} \quad (2)$$

$$gie_{it} = \gamma_0 + \gamma_1 lep_{it} + \sum\nolimits_k \gamma_k control_{it}^k + \varepsilon_{it} \quad (3)$$

$$gie_{it} = \delta_0 + \delta_1 fd_{it} + \delta_2 lep_{it} + \sum\nolimits_k \delta_k control_{it}^k + \varepsilon_{it} \quad (4)$$

Among them, lep_{it} is mediator variable, representing the environmental protection preference of local governments. If δ_1 and δ_2 are both significant, then the fiscal decentralization both have a directly affect and an indirectly impact through the mediator variable to the regional GIE.

Variable measurement and explanation

Calculation of regional GIE

Based on the research experience before, we selected the non-radial, non-angular, and general return-to-scale SBM model in the DEA method to measure the regional GIE, and selected the following indicators as input and output indicators.

Input indicators: Due to the lack of direct input data on green innovation, we draw on the practice of most studies (Xu X G & Zhou Y F, 2021; Long R Y et al., 2020; Liu C Y et al., 2019) and took the regional full-time equivalent of research and experimental development (R&D) personnel and their internal expenditures as input variables respectively in order to reflect the innovation dimension. At the same time, we added the total investment in regional environmental pollution control as a variable of capital investment to reflect the green dimension.

Output indicators: Most of the previous studies used variables such as the number of patent applications, new product sales revenue, and environmental pollution index as output indicators. However, since the number of patent may not be able to accurately reflect green innovation, we selected the number of green patents (that is, the total number of green inventions and green utility models obtained in the year) as one of the output indicators to more accurately reflect the local level of green innovation. In addition, the sales revenue of new products of industrial enterprises was selected as the second output indicator to reflect the degree of product innovation. Finally, refer to Liu C Y et al. (2019), the entropy method (see Eqs. (8)–(12) in Appendix) was used to calculate the comprehensive index of newly added wastewater and waste gas design and treatment capacity of industrial pollution prevention and control investment projects completed this year as the third output index to reflect the regional pollution prevention and treatment capacity.

The input–output indicator system is summarized in Table 1.

According to the input–output index system and SBM model in Table 1, we used the DEA-solver software to calculate the GIE values (see Table 14 in Appendix).

Independent variables

In the past studies, there were mainly three methods to measure fiscal decentralization, namely, revenue level, expenditure level, and fiscal freedom level (Hao et al. 2020; Ji et al. 2021; Zhang et al. 2017). These three different methods may led to different empirical results. Considering this problem, we selected the above three indicators for measurement at the same time. The specific calculation methods are as follows.

$$\text{Decentralization of Fiscal Expenditure} = \frac{\text{General budget expenditure percapita of local finance}}{\text{Fiscal expenditure per capita at the central level}}$$

$$\text{Decentralization } of \text{ Fiscal Revenue} = \frac{\text{General budgetary revenue percapita } of \text{ local finance}}{\text{Fiscal revenue per capita at the central level}}$$

$$\text{Decentralization of Fiscal Freedom} = \frac{\text{General budget revenue of local finance}}{\text{General budget expenditure of local finance}}$$

Table 1 GIE measurement index system

Input indicator	Staff input	Regional full-time equivalent of R&D personnel
	Capital investment	Regional internal expenditure on R&D funding
		Total investment in environmental pollution control
Output indicator	Green patent	The number of green patents in the region (that is, the total number of green inventions and green utility models obtained in the year)
	Product results	Regional new product sales revenue of industrial enterprises above the designated size
	Pollution treatment	Comprehensive index of new wastewater and waste gas design treatment capacity for industrial pollution prevention and control investment projects completed in the year (in entropy method)

Mediator variable

The mediator variable was the local government's environmental protection preference, which reflected their emphasis on strengthening local environmental protection construction. Considering the fiscal environmental protection expenditure is correlated with the investment in environmental pollution which is one of the input indicators in the calculation of GIE, we used environmental protection publicity and education activities as the mediator variable. Actually, in China, these activities are mainly promoted by local governments and carried out in communities, schools and other places. Therefore, the more propaganda and education activities, the higher concentrations on environmental protection construction, and thus the stronger the preference for environmental protection.

Control variables

According to the past study, we chose control variables of six dimensions as economic development, industrial structure, human capital, city development, high-tech enterprise development, and energy consumption. Specifically, these control variables include the actual per capita GDP and its quadratic term, the actual added value of the tertiary industry, the number of ordinary colleges and universities, the urban registered unemployment rate, the urban population density, the regional proportion of high-tech enterprises, and the per capita electricity consumption.

Table 2 Descriptive statistics

Variable name	Variable meaning	Mean	Standard deviation	Minimum	Medium	Maximum	Number of samples
*gie*_1	Regional GIE (SBM model)	0.688	0.238	0.246	0.644	1.000	270
*gie*_2	Regional GIE (three-stage DEA model)	0.938	0.067	0.735	0.957	1.000	270
*gie*_3	Regional GIE (SBM model with lagged output)	0.543	0.322	0.059	0.414	1.000	270
*gie*_4	Regional GIE (SBM model with undesirable output)	0.558	0.280	0.059	0.471	1.000	270
*fd*_1	Decentralization of fiscal expenditure	5.888	2.827	2.307	5.113	14.596	270
*fd*_2	Decentralization of fiscal revenue	1.171	0.934	0.357	0.853	4.786	270
*fd*_3	Decentralization of fiscal freedom	0.521	0.199	0.148	0.455	0.951	270
*lep*_1	Number of social and environmental publicity and education activities carried out in the current year (log)	5.492	1.068	0.000	5.535	8.732	270
*lep*_2	Number of environmental monitoring instruments per unit area of environmental monitoring room	0.094	0.043	0.008	0.088	0.275	270
rgdp	Real GDP per capita	3.340	1.761	0.794	2.844	8.600	270
*rgdp*2	Square of real GDP per capita	14.241	15.618	0.631	8.089	73.954	270
ravti	Real added value of the tertiary industry (log)	8.363	0.933	5.687	8.435	10.311	270
college	Number of regular colleges and universities (log)	4.144	0.778	1.792	4.369	5.088	270
unempr	Urban registered unemployment rate	3.501	0.639	1.200	3.600	4.600	270
popd	Urban population density	2773.641	1240.826	622.000	2548.500	5967.000	270
htetp	The proportion of the number of high-tech industrial enterprises	0.197	0.805	0.002	0.049	5.922	270
econsum	Electricity consumption per capita	0.384	0.229	0.117	0.313	1.315	270
imex	The total import and export volume of the location of the business unit per GDP	4775.819	5663.604	542.681	2098.361	24,444.805	270
citinc	Per capita real disposable income of urban residents	18,281.423	6109.113	10,012.000	17,211.859	42,783.262	270
einvest	Investment in urban environmental infrastructure construction per unit of GDP	0.008	0.005	0.001	0.007	0.027	270
wgas	Total industrial exhaust emissions (log)	9.567	0.791	7.017	9.613	11.279	270

Data sources and descriptive statistics

Sample selection and data sources

We selected 30 provinces (include autonomous regions and municipalities directly under the central government) in mainland China from 2007 to 2015 as the sample. The main data sources are China Statistical Yearbook, China Science and Technology Statistical Yearbook, China Fiscal Yearbook, China Research Data Service Platform (CNRDS), etc. In addition, in order to eliminate the influence of inflation, we took 2007 as the constant price, and used the GDP deflator to preprocess the economic data.

Variable descriptive statistics

Table 2 lists the descriptive statistics of the variables.

Results

Basic results

Since the GIE data have the nature of interception, we used the Tobit model to regress Eq. (1). The results are shown in Table 3, where the independent variable in columns (1)–(2) were decentralization of fiscal expenditure, while decentralization of fiscal revenue in columns (3)–(4) and decentralization of fiscal freedom in columns (5)–(6). The results showed that the coefficients of all the independent variables were positively significant at the 5% level, indicating that fiscal decentralization had a positive impact on regional GIE. The main reason for this impact may be that under the guidance of China's green and innovative development strategy, local officials were motivated to improve the regional GIE, actively promote environment protection, and leverage scientific and technological innovation as long-term drivers of economic growth to achieve high-quality regional

Table 3 Basic regression

	(1)	(2)	(3)	(4)	(5)	(6)
	gie_1					
fd_1	0.042***	0.034**				
	(5.70)	(2.36)				
fd_2			0.140***	0.109**		
			(6.14)	(2.24)		
fd_3					0.534***	0.713***
					(5.45)	(3.99)
rgdp		−0.000		0.036		0.029
		(−0.01)		(0.55)		(0.46)
rgdp2		0.003		−0.002		0.000
		(0.49)		(−0.25)		(0.06)
ravti		−0.009		−0.060		−0.141***
		(−0.16)		(−1.29)		(−2.90)
college		−0.065		−0.042		−0.030
		(−1.37)		(−0.88)		(−0.65)
unempr		−0.088***		−0.088***		−0.079**
		(-2.67)		(−2.67)		(−2.49)
popd		−0.000**		−0.000		−0.000
		(−2.32)		(−1.65)		(−0.58)
htetp		−0.098***		−0.088***		−0.086***
		(−2.92)		(−2.63)		(−2.65)
econsum		−0.320***		−0.165		−0.110
		(−2.62)		(−1.43)		(−0.97)
_cons	0.495***	1.396***	0.578***	1.654***	0.460***	1.925***
	(10.88)	(4.03)	(18.72)	(5.57)	(8.62)	(7.11)
N	270	270	270	270	270	270
Log likelihood	−113.628	−95.876	−110.651	−96.109	−116.104	−90.826

The parentheses are *t* statistics. *, **, and *** indicate significant at the 10%, 5%, and 1% levels, respectively

economic growth. Fiscal decentralization could reasonably allocate financial resources between governments with different levels, so that local governments could obtain financial autonomy to some degree, and promote the improvement of regional GIE.

Mechanisms

In the above analysis, we mentioned that local government officials were motivated to improve the regional GIE. Fiscal decentralization enabled local governments to gain higher autonomy in the allocation of financial resources, so that they could allocate financial funds more flexibly according to their own preferences and realized their own development focus. Therefore, local government environmental preference may be an important mechanism that fiscal decentralization could positively influence regional GIE. In order to test this effect, we took local government environmental preference as the mediator variable and regress in Eq. (2).

The results are shown in Table 4, where the dependent variable in column (1) was the logarithm of the number of social environmental propaganda and education activities carried out in the current year. It could be seen that fiscal expenditure decentralization had a significant positive impact on local government environmental protection preferences, which is consistent with the previous research (Kuai P et al. 2019). To be specific, local government officials were motivated to improve regional GIE, especially since the central government clearly proposed the national strategy of green and innovative development, so the local governments have placed environmental protection in an increasingly important position, constantly regulating the development and utilization of resources, controlling pollution emissions, and improving the public participation system. Driven by such development strategies and local sustainable development demands, local governments had an increasingly strong preference for strengthening environmental protection construction, and fiscal decentralization can provide flexible funding guarantees for local governments to carry out environmental protection work according to local conditions, making local governments with higher fiscal autonomy prefer to increase environmental protection behaviors represented by publicity and education activities. In columns (2) and (3), the dependent variable was the regional GIE measured by the SBM model. The regression in Eq. (3) showed in columns (2) indicated that the social environmental propaganda and education activities had a positive impact on the regional GIE. The reason for this result may be that local governments with strong environmental protection preferences would send a signal to the society that they attach importance to green development by carrying out more social environmental publicity and education activities, leading the construction of regional environmental protection, improving residents' environmental protection awareness, providing a social foundation for regional green innovation activities, driving social resources to invest in environmental protection, strengthening green technology research, and then raising the regional GIE. Finally, we included both fiscal decentralization and local government environmental protection preferences into the independent variables, and performed regression analysis in Eq. (4). As can be seen in columns (3), after controlling for local government environmental protection preferences, fiscal

Table 4 Mediation effect test

	(1)	(2)	(3)
	lep_1	*gie_1*	*gie_1*
fd_1	0.082*		0.032**
	(1.88)		(2.19)
lep_1		0.039**	0.034*
		(1.99)	(1.77)
rgdp	−0.040	0.049	0.000
	(−0.20)	(0.75)	(0.00)
rgdp2	−0.008	0.003	0.003
	(−0.40)	(0.49)	(0.54)
ravti	0.702***	−0.093**	−0.032
	(4.33)	(−1.97)	(−0.59)
college	0.017	−0.056	−0.064
	(0.11)	(−1.20)	(−1.36)
popd	−0.000	−0.000*	−0.000**
	(−1.30)	(−1.67)	(−2.20)
unempr	0.075	−0.103***	−0.090***
	(0.78)	(−3.21)	(−2.77)
htetp	0.114	−0.098***	−0.101***
	(1.08)	(−2.94)	(−3.03)
econsum	0.049	−0.222*	−0.319***
	(0.13)	(−1.96)	(−2.63)
_cons	−0.798	1.877***	1.415***
	(−0.77)	(6.78)	(4.12)
N	270	270	270
Log likelihood	−355.693	−96.732	−94.327

The parentheses are t statistics. *, **, and *** indicate significant at the 10%, 5%, and 1% levels, respectively

Table 5 Bootstrap results

	Observed coefficient	Bias	Bootstrap std. err	95% conf. interval (BC)	
Indirect effect	0.0022	−0.0003	0.0026	0.0010	0.0087
Direct effect	0.0170	−0.0061	0.0080	0.0021	0.0247

Table 6 Robustness test of three-stage DEA model

	(1)	(2)	(3)	(4)	(5)	(6)
	gie_2					
fd_1	0.009***	0.016***				
	(3.99)	(3.78)				
fd_2			0.016**	0.051***		
			(2.46)	(3.66)		
fd_3					0.002	0.130**
					(0.05)	(2.47)
_cons	0.907***	1.200***	0.939***	1.315***	0.957***	1.449***
	(66.37)	(11.91)	(98.98)	(15.15)	(57.17)	(17.38)
Control variables	No	Yes	No	Yes	No	Yes
N	270	270	270	270	270	270
Log likelihood	107.480	139.876	102.319	139.773	99.220	135.758

The *t*-statistics in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively

Table 7 Robustness test of mediation effect-three-stage DEA model

	(1)	(2)	(3)
	lep_1	*gie_2*	*gie_2*
fd_1	0.082*		0.015***
	(1.88)		(3.62)
lep_1		0.012**	0.010*
		(2.07)	(1.76)
_cons	−0.798	1.426***	1.202***
	(−0.77)	(17.24)	(12.06)
Control variables	Yes	Yes	Yes
N	270	270	270
Log likelihood	−355.693	134.829	141.408
Bootstrap results	[0.0001, 0.0014]		

The *t*-statistics in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively

decentralization still had a significant positive impact on regional GIE.

Besides, for the purpose of enhancing the credibility of the above conclusion, Bootstraps method was used for further test, and the results are in Table 5 where both the indirect effect and the direct effect were significantly positive. Therefore, local government environmental protection preference indeed played an important intermediary role.

Discussion

Three-stage DEA model

The three-stage DEA model can eliminate the influence of environmental and random factors while the SBM model cannot. So we remeasured the regional GIE through three-stage DEA model for some more accurate results. First,

Table 8 Robustness test of regional GIE

	(1)	(2)	(3)	(4)	(5)	(6)
	gie_3			*gie_4*		
fd_1	0.049***			0.005		
	(3.81)			(0.54)		
fd_2		0.102**			0.152***	
		(2.40)			(4.83)	
fd_3			0.242			0.787***
			(1.41)			(6.44)
_cons	1.345***	1.876***	2.111***	0.579**	0.343*	0.731***
	(4.36)	(7.26)	(8.63)	(2.40)	(1.80)	(4.20)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
N	270	270	270	270	270	270
Log likelihood	−29.415	−33.626	−35.494	37.279	48.318	56.402

The *t*-statistics in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively

Table 9 Robustness test of mediation effect-recalculation of regional GIE

	(1)	(2)	(3)	(4)	(5)
	lep_1	*gie_3*	*gie_3*	*gie_4*	*gie_4*
fd_1	0.082*		0.047***		0.003
	(1.88)		(3.59)		(0.30)
lep_1		0.042**	0.035*	0.030**	0.029**
		(2.30)	(1.93)	(2.11)	(2.07)
_cons	−0.798	2.072***	1.372***	0.648***	0.602**
	(−0.77)	(8.53)	(4.47)	(3.50)	(2.52)
Control variables	Yes	Yes	Yes	Yes	Yes
N	270	270	270	270	270
Log likelihood	−355.693	−33.855	−27.558	39.349	39.395
Bootstrap results	[0.0001, 0.0048]			[0.0005, 0.0078]	

The *t*-statistics in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively

it is requisite to bring environmental variables into the regression model. Here, we selected the GDP per capita, the proportion of people with college education or above, and the comprehensive index synthesized by industrial wastewater discharge, waste gas discharge, and solid waste production with entropy method as the environmental variables. These above three environmental variables would have a certain impact on the regional GIE, but they were not easily changed by local governments in the short term so that satisfy the "separation assumption." In order to eliminate the dimensional influence, we standardized the above three environmental variables. After three stages of processing, the new regional GIE values from 2007 to 2015 are showed in Table 15.

Then, we used the new GIE value as the dependent variable to re-regress Eq. (1) and the results are shown in Table 6. It is obviously that whether it was fiscal expenditure decentralization (columns (1)–(2)), fiscal revenue decentralization (columns (3)–(4)), or fiscal freedom decentralization (columns (5)–(6)), their impact on regional GIE were still significant, which once again verified our previous conclusions.

Then, we tested the mediation effect again which can be seen in Table 7. Once again, we came to the same conclusion as before. Besides, the bias adjusted confidence interval from bootstrap result can be seen in the last row, which verified the existence of mediation effect again.

Other recalculation of regional GIE

However, in the previous calculation of regional GIE, we used input variables and output variables in both the current period, but the input may rarely produce output immediately. Therefore, considering the output of innovation activities usually have a strong lag; we recalculated the regional GIE with current period input variables and one lag period output variables through SBM model; then, the regression results are shown in columns (1)–(3) in

Table 10 Robustness test of mediator variables

	(1)	(2)	(3)	(4)	(5)
	lep_2	*gie_1*	*gie_1*	*gie_2*	*gie_2*
fd_1	0.002		0.033**		0.016***
	(1.40)		(2.26)		(3.71)
lep_2		1.268**	1.205**	0.343**	0.319**
		(2.26)	(2.15)	(2.13)	(2.01)
_cons	0.225***	1.612***	1.149***	1.359***	1.133***
	(6.00)	(5.29)	(3.17)	(14.94)	(10.72)
Control variables	Yes	Yes	Yes	Yes	Yes
N	270	270	270	270	270
Log likelihood	539.864	−96.098	−93.531	135.012	141.933
Bootstrap results		[0.0002, 0.0023]		[0.0003, 0.0006]	

The *t*-statistics in parentheses. ** and *** indicate significance at the 5% and 1% levels, respectively

Table 11 Mediating effect test considering endogenous variables

	(1)	(2)	(3)
	lep_1	*gie_1*	*gie_2*
mean_lep_1	−1.094***		
	(-3.26)		
lep_1		0.181*	0.079**
		(1.66)	(2.22)
fd_1	0.114**	0.020	0.010*
	(2.56)	(1.12)	(1.68)
_cons	4.393**	1.516***	1.245***
	(2.32)	(3.93)	(9.89)
Control variables	Yes	Yes	Yes
N	270	270	270
Prob > F	0.000		
Wald test of exogeneity: Prob > chi²		0.128	0.011
Adj R-squared	0.284		

The *t*-statistics in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively

Table 8. Besides, in the above analysis, in order to reflect the regional pollution prevention and treatment capacity, we used the entropy method to calculate a comprehensive index of the newly added wastewater and waste gas design and treatment capacity of the industrial pollution prevention and control investment project as the third output index, and then calculate the regional GIE. In order to avoid the impact of the probable calculation errors on the results, we considered the production volume of general industrial solid waste as the non-expected output index and recalculated regional GIE through SBM model. After that, the regression results can be seen in columns (4)–(6) in Table 8. Although a few of coefficients are not statistically significant, all coefficients are positive, which proved that fiscal decentralization has a positive and robust impact on regional GIE.

Moreover, the mediation effect can be seen in Table 9, which are consistent with the previous results.

Other measurement of mediator variable

As a conceptual effort, social environmental propaganda and education activities may need a relatively long process to affect the regional environmental quality, while direct environmental detection could obtain local environmental quality information more quickly and effectively. Therefore, we changed the measurement method of mediator variable into the number of environmental monitoring instruments per unit of environmental monitoring area. In China, for the purpose of maximizing profits, enterprises would not spontaneously choose to detect environmental quality. So, environmental monitoring was mainly carried out by local governments or by enterprises under the governments' requests. The larger the number of environmental monitoring instruments, the greater the intensity of regional environmental management, which could reflect the stronger environmental preferences of local governments. The regression results are shown in Table 10. The last row reported the bias adjusted confidence interval from bootstrap result. Regardless of the regional GIE value calculated by SBM model or three-stage DEA model, the results were agree with the previous conclusion.

Endogeneity

In the previous analysis, we confirmed that fiscal decentralization improved the regional GIE by increasing local government environmental protection preferences. However, under China's government official promotion tournament mechanism, in regions with higher regional GIE, local governments

Table 12 Heterogeneity analysis—2007 to 2010

	(1)	(2)`	(3)	(4)	(5)	(6)
	gie_1	*gie_1*	*gie_1*	*gie_2*	*gie_2*	*gie_2*
fd_1	−0.023			0.006		
	(-0.79)			(0.86)		
fd_2		−0.045			0.016	
		(−0.46)			(0.75)	
fd_3			0.803***			0.036
			(2.87)			(0.52)
_cons	1.925***	1.727***	1.813***	1.119***	1.161***	1.192***
	(3.54)	(3.85)	(4.28)	(8.80)	(10.79)	(11.43)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
N	120	120	120	120	120	120
Log likelihood	−38.472	−38.675	−34.703	76.884	76.798	76.649

The *t*-statistics in parentheses. *** indicate significance at the 1% level

Table 13 Heterogeneity Analysis-2011 to 2015

	(1)	(2)	(3)	(4)	(5)	(6)
	gie_1	*gie_1*	*gie_1*	*gie_2*	*gie_2*	*gie_2*
fd_1	0.068***			0.027***		
	(3.14)			(3.92)		
fd_2		0.255***			0.084***	
		(2.77)			(2.95)	
fd_3			1.243***			0.202**
			(4.00)			(2.02)
_cons	0.583	1.468***	2.289***	1.009***	1.404***	1.634***
	(1.00)	(3.40)	(5.89)	(5.55)	(10.28)	(12.37)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
N	150	150	150	150	150	150
Log likelihood	−48.941	−50.052	−46.310	76.631	72.981	70.511

The *t*-statistics in parentheses. ** and *** indicate significance at the 5% and 1% levels, respectively

Table 14 GIE value-SBM model

	2007	2008	2009	2010	2011	2012	2013	2014	2015
Beijing	0.5370	0.6259	1.0000	0.5646	0.6869	1.0000	1.0000	1.0000	1.0000
Tianjin	1.0000	1.0000	1.0000	1.0000	0.7020	1.0000	1.0000	0.7115	0.8366
Hebei	0.4737	0.4738	0.4218	0.4476	0.4264	0.5190	0.4807	0.5124	0.4841
Shanxi	0.4356	0.3842	0.3358	0.3811	0.4070	0.4137	0.3741	0.4190	0.3924
Inner Mongolia	0.4322	0.3014	0.3096	0.3192	0.2825	0.2870	0.2463	0.2710	0.2646
Liaoning	0.5564	0.6397	0.6444	0.5737	0.5539	0.4939	0.5326	0.5708	0.5266
Jilin	0.6681	0.7881	1.0000	0.7527	1.0000	1.0000	0.3857	0.5756	0.5607
Heilongjiang	0.7185	0.4411	0.3642	0.3927	0.3606	0.3720	0.3000	0.3234	0.3066
Shanghai	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.7078
Jiangsu	0.5704	0.6581	0.8489	0.8159	0.8862	0.9278	0.7900	0.8602	0.7421
Zhejiang	0.8014	0.9070	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Anhui	0.4886	0.4033	0.4661	0.6137	0.6833	0.6921	0.5859	0.6786	0.6639
Fujian	0.6042	0.6430	0.6770	0.7044	0.6648	0.6501	0.5278	0.5913	0.6171
Jiangxi	0.4873	0.5173	0.3861	0.4467	0.4584	0.5284	0.5155	0.5660	0.5777
Shandong	0.6438	0.6196	0.8365	0.8604	0.7449	0.9305	0.8574	0.6874	0.6146
Henan	0.6436	0.6479	0.6125	0.6216	0.6109	0.5650	0.5723	0.6106	0.5961
Hubei	0.6638	0.7036	0.5423	0.5716	0.5104	0.5561	0.5638	0.5800	0.5990
Hunan	0.6532	0.7456	0.6643	0.7468	0.8228	1.0000	1.0000	1.0000	0.6542
Guangdong	1.0000	1.0000	1.0000	0.8888	0.8868	1.0000	1.0000	1.0000	1.0000
Guangxi	0.8056	0.5700	0.5058	0.4855	0.5189	0.5576	0.5584	0.6214	0.6640
Hainan	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Chongqing	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Sichuan	0.5464	0.6308	0.6485	0.6027	0.6601	0.5930	0.6519	0.5420	0.5785
Guizhou	1.0000	1.0000	1.0000	1.0000	0.7937	0.7927	0.5315	1.0000	1.0000
Yunnan	0.7662	0.5498	1.0000	0.4023	1.0000	0.5984	0.4354	1.0000	0.3932
Shaanxi	0.3380	0.3083	0.2661	0.3591	0.4038	0.3716	0.3436	0.3624	0.2952
Gansu	0.4494	0.4732	0.3396	0.5194	0.6530	0.6191	0.4656	0.5099	0.4522
Qinghai	1.0000	0.5884	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Ningxia	0.2979	0.4335	0.6276	0.5996	0.6396	0.8133	1.0000	0.6606	0.7191
Xinjiang	0.4588	0.5969	0.3976	1.0000	0.5200	0.5235	0.4955	1.0000	0.7350
National average	0.6680	0.6550	0.6965	0.6890	0.6959	0.7268	0.6738	0.7218	0.6660
minimum	0.2979	0.3014	0.2661	0.3192	0.2825	0.2870	0.2463	0.2710	0.2646
Eastern average	0.7443	0.7788	0.8571	0.8050	0.7774	0.8656	0.8353	0.8121	0.7754
Central average	0.5948	0.5789	0.5464	0.5659	0.6067	0.6409	0.5372	0.5942	0.5438
Western average	0.6450	0.5866	0.6450	0.6625	0.6792	0.6506	0.6117	0.7243	0.6456

may tend to further strengthen their investment in green innovation development to promote long-term and high-quality economic growth. Therefore, the larger the regional GIE, the deeper environmentally friendly the local government may have. To release the possible endogeneity problems, we used the mean value of local government environmental protection preference variables of other provinces in that year as an instrumental variable for local government environmental protection preference variables of this province. The main reason for choosing this instrument variable was that under the promotion competition among local officials, the environmental protection preferences of local governments in other regions might had a significant impact on local governments, resulting in "top-to-top competition" or "bottom-to-bottom competition" in environmental regulation behavior (Kim and Rhee 2019; Prakash and Potoski 2010). Therefore, we chose the mean value of local government environmental protection preference variables of other provinces in the current year as the instrumental variable, and used the two-step IV Tobit model for regression as can be seen in Table 11. Here, *mean_lep_1* represented the mean value of the logarithm of the number of social environmental propaganda and education activities carried out by other provinces in that year. Column (1) was the first-stage regression result. The instrumental variable had a significant negative impact on the province's environmental protection preference, which confirmed the validity of the instrumental variable. Columns (2)–(3) were the second-stage regression results, and the dependent variable in column (2) was the regional GIE measured by the SBM model while in column (3) was the regional GIE measured by the three-stage DEA model. From the results, we can see that the local government's environmental protection preference still played an important mediating role, which was consistent with the previous conclusion.

Table 15 GIE value-three-stage DEA model

	2007	2008	2009	2010	2011	2012	2013	2014	2015
Beijing	0.933	0.923	1.000	0.992	1.000	1.000	1.000	1.000	1.000
Tianjin	1.000	1.000	1.000	0.912	0.850	0.955	0.989	0.925	0.777
Hebei	0.910	0.929	0.938	0.933	0.836	0.901	0.781	0.794	0.752
Shanxi	0.843	0.965	0.967	0.951	0.831	0.915	0.789	0.878	0.917
Inner Mongolia	0.843	0.961	0.956	0.938	0.901	0.89	0.771	0.778	0.735
Liaoning	0.929	0.987	0.968	0.946	0.950	0.872	0.923	0.819	0.818
Jilin	0.857	0.973	1.000	0.983	1.000	1.000	0.881	0.963	0.953
Heilongjiang	0.940	1.000	0.974	0.937	0.851	0.951	0.932	0.925	0.893
Shanghai	1.000	1.000	1.000	1.000	1.000	1.000	0.946	0.985	0.845
Jiangsu	0.876	0.881	0.873	0.870	1.000	1.000	0.903	0.973	0.905
Zhejiang	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Anhui	0.853	0.889	0.893	0.916	0.929	0.967	0.897	0.962	0.942
Fujian	0.923	0.919	0.962	0.954	0.927	0.894	0.849	0.827	0.909
Jiangxi	0.880	0.884	0.921	0.924	0.872	0.949	0.950	0.873	0.924
Shandong	0.965	0.839	0.990	1.000	1.000	1.000	1.000	0.975	0.839
Henan	1.000	0.992	0.985	0.927	0.884	0.858	0.843	0.828	0.861
Hubei	0.909	0.964	0.924	0.838	0.781	0.82	0.816	0.796	0.791
Hunan	0.920	0.982	0.941	0.917	0.893	1.000	1.000	1.000	1.000
Guangdong	1.000	1.000	0.921	1.000	0.907	0.866	0.764	0.822	0.848
Guangxi	1.000	1.000	1.000	0.952	0.950	0.971	0.955	0.972	0.992
Hainan	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.994
Chongqing	0.936	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Sichuan	0.934	0.924	0.882	0.924	0.975	0.891	0.959	0.875	0.917
Guizhou	1.000	1.000	1.000	0.990	0.937	0.982	1.000	1.000	1.000
Yunnan	0.852	0.977	1.000	0.977	1.000	0.996	0.965	1.000	0.938
Shaanxi	0.841	0.841	0.829	0.812	0.832	0.803	0.814	0.887	0.803
Gansu	0.812	0.950	0.958	0.958	0.934	0.976	0.956	0.961	0.941
Qinghai	0.961	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Ningxia	0.962	1.000	1.000	0.992	0.993	0.992	1.000	1.000	1.000
Xinjiang	0.878	1.000	0.998	1.000	0.983	1.000	0.999	1.000	1.000
National average	0.925	0.959	0.963	0.951	0.934	0.948	0.923	0.927	0.910
Minimum	0.812	0.839	0.829	0.812	0.781	0.803	0.764	0.778	0.735
Eastern Average	0.878	0.873	0.888	0.884	0.873	0.874	0.846	0.843	0.807
Central Average	0.900	0.956	0.951	0.924	0.880	0.933	0.889	0.903	0.910
Western Average	0.911	0.968	0.966	0.958	0.955	0.955	0.947	0.952	0.939

Further discussion

In the previous analysis, we mentioned that these effects may be closely related to the guidance of the national development strategy, and the "Twelfth Five-Year Plan" was an important guiding direction of China's economic and social development from 2011 to 2015 which incorporated green development and innovative development into the national development strategy. Driven by the national strategy, local officials had great incentives to closely follow the direction of the national development strategy and actively promote regional environmental protection and technological innovation. Therefore, according the time of "Twelfth Five-Year Plan," we divided the analyses into two parts including 2007 to 2010 and 2011 to 2015 as can be seen in Tables 12 and 13, respectively. In Table 12, from 2007 to 2010, only fiscal freedom decentralization had a significant positive effect on the regional GIE. From Table 13, it could be seen that from 2011 to 2015, the impact was significant at the level of 1%, which means that after the guidance of national strategy, local governments had greater incentives to strengthen regional green development and innovative development, so the estimation results became significant. Therefore, the direction of the national development strategy would guide the behavior of local governments, so that fiscal decentralization can make sense in the improving of regional GIE.

Conclusion

As an important system for inter-government coordination of resource allocation, the fiscal system would affect regional green innovation activities by affecting the behavior of local governments. Based on the provincial data in China, this paper analyzed the impact of fiscal decentralization on the regional GIE and the mechanism of local government environmental protection preferences. Here are the research conclusions.

First, fiscal decentralization had a significant positive impact on regional GIE. Under the guidance of the green and innovative development strategy, local officials were motivated to improve the regional GIE to promote environmental protection, sustainable development and technological innovation, so as to achieve long-term high-quality growth of the regional economy. Fiscal decentralization could give local governments partial control over financial resources, and ensure that local governments play an effective role in green innovation according to local situations, thereby promoting the improvement of regional GIE.

Second, local governments' preference in environmental protection played an important intermediary role, and fiscal decentralization affected regional GIE by influencing their preference. With the increasing attention of environmental accomplishments in the evaluation system, local governments had a stronger preference for strengthening environmental protection, leading the construction of more social environmental propaganda and education activities and purchasing more environmental monitoring instruments, thereby improving the regional GIE.

Third, the direction of the national development strategy guides the governments behavior in China. With the green and innovative development concept brought into the national development strategy, local governments had greater motivation to actively promote regional environmental protection and technological innovation. In 2010 and before, the impact of fiscal decentralization on regional GIE relatively limited. After 2011, the impact became significantly positive.

Appendix

The SBM model is represented as follows:

$$\min_{\lambda,s^-,s^+} \rho = \frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{i0}}}{1+\frac{1}{s}\sum_{r=1}^{s}\frac{s_r^+}{y_{r0}}} \tag{5}$$

$$\text{subject to } x_{i0} = \sum_{j=1}^{n} X_{ij}\lambda_j + s_i^-, i = 1,2,...,m$$

$$y_{r0} = \sum_{j=1}^{n} Y_{rj}\lambda_j - s_r^+, r = 1,2,...s$$

$$\lambda_j \geq 0, s_i^- \geq 0, s_r^+ \geq 0$$

ρ in Eq. (5) represents the efficiency value. $0 < \rho \leq 1$. m and s are the total number of input and output indicators respectively, and $X_{rj}\,Y_{rj}$ are the input and output amounts of the jth decision-making unit for the ith input indicator and the rth output indicator, respectively. λ_j are the weights, and s_i^- and s_r^+ are the slack variables for input and output, respectively.

The evaluation process of three-stage DEA model can be divided into three stages as follows.

First, a traditional DEA model is used and the slack variables of the relevant indicators are obtained.

Second, the effects of environmental variables are estimated using the stochastic frontier analysis (SFA) method as:

$$s_{ij} = f^j(z_i, \beta^j) + \nu_{ij} + \mu_{ij} \quad (i = 1,2,3,...,n; j = 1,2,3,...,p) \tag{6}$$

In formula (6), s_{ij} represents the slack variable of the jth input of the ith decision-making unit. $z_i = (z_{1i}, z_{2i}, ..., z_{ki})$ represents the value of the kth environmental variable. β^j is the parameter to be estimated for the jth input. $\nu_{ij} + \mu_{ij}$ is the compound error term, while ν_{ij},represents the random errors, and $\nu_{ij}\ N(0, \sigma_{jv}^2)$. μ_{ij} indicate management inefficiencies, and $\mu_{ij} \sim N^+(\mu_j, \sigma_{ju}^2)$. μ_{ij} and ν_{ij} are independent of each other.

Subsequently, the input amount was adjusted as follows.

$$x_{ij}^{A} = x_{ij} + \left[\max\left[f^{j}\left(z_i, \widehat{\beta^{j}}\right)\right] - f^{j}\left(z_i, \widehat{\beta^{j}}\right)\right] + \left[\max\left(\widehat{v}_{ij}\right) - \widehat{v}_{ij}\right] \quad (i = 1, 2, 3, ..., n; j = 1, 2, 3, ...p) \tag{7}$$

In formula (7), x_{ij}^{A} is the input after adjustment, and x_{ij} is the input before adjustment.

Third, the efficiency value is recalculated using the adjusted relevant variables and the traditional DEA model.

The calculation steps of entropy method are as follows:

First, the original data are standardized to eliminate the dimensional differences between each indicator, and then, the standardized value of kth indicator X_{itk} in year t of province i is obtained:

$$\theta_{itk} = \begin{cases} \frac{X_{itk} - \min(X_{itk})}{\max(X_{itk}) - \min(X_{itk})}, if X_{itk} \text{ is a positive indicator} \\ \frac{\max(X_{itk}) - X_{itk}}{\max(X_{itk}) - \min(X_{itk})}, if X_{itk} \text{ is a negative indicator} \end{cases} \tag{8}$$

$$\widetilde{\theta_{itk}} = \begin{cases} \theta_{itk}, if \theta_{itk} \neq 0 \\ \theta_{itk} + 10^{-4}, if \theta_{itk} = 0 \end{cases} \tag{9}$$

Second, we can calculate the entropy of each standardized index:

$$E_k = -\frac{1}{\ln(n)} \sum_{i=1}^{n} \left[\frac{\widetilde{\theta_{itk}}}{\sum_{i=1}^{n} \widetilde{\theta_{itk}}} \times \ln\left(\frac{\widetilde{\theta_{itk}}}{\sum_{i=1}^{n} \widetilde{\theta_{itk}}} \right) \right] \tag{10}$$

where n represents the sample size.

Third, the entropy weight of the kth index is:

$$W_k = \frac{1 - E_k}{\sum_{k=1}^{m} \left(1 - E_k\right)} \tag{11}$$

Finally, the weighted composite index γ_{it} is:

$$\gamma_{it} = \sum_{k=1}^{m} W_k \times \widetilde{\theta_{itk}} \tag{12}$$

Please see Table 14, and 15

Due to missing data, the statistical scope of this table does not include Hong Kong, Macao, Taiwan, and Tibet

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Data availability The datasets supporting the results of this article are included within the article and its additional files.

Declarations

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